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Effect of dietary betaine on nutrient utilization and partitioning in the young growing feed-restricted pig[1–4]

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ABSTRACT: The purpose of this study was to examine the effects of dietary betaine over a range of concentrations (between 0 and 0.5%) on growth and body composition in young feed-restricted pigs. Betaine is associated with decreased lipid deposition and altered protein utilization in finishing pigs, and it has been suggested that the positive effects of betaine on growth and carcass composition may be greater in energy-restricted pigs. Thirty-two barrows (36 kg, n = 8 pigs per group) were restrictively fed one of four corn-soybean meal-skim milk based diets (18.6 % crude protein, 3.23 Mcal ME/kg) and supplemented with 0, 0.125, 0.25, or 0.5% betaine. Feed allotment was adjusted weekly according to BW, such that average feed intake was approximately 1.7 kg for all groups. At 64 kg, pigs were slaughtered and visceral tissue was removed and weighed. Carcasses were chilled for 24 h to obtain carcass measurements. Subsequently, one-half of each carcass and whole visceral tissue were ground for chemical analysis. Linear regression analysis indicated that, as betaine content of the diet was elevated from 0 to 0.5%, carcass fat concentration ($P = 0.06$), P3 fat depth ($P = 0.14$) and viscera weight ($P = 0.129$) were decreased, whereas total carcass protein ($P = 0.124$), protein deposition rate ($P = 0.98$), and lean gain efficiency ($P = 0.115$) were increased. The greatest differences over control pigs were observed in pigs consuming 0.5 % betaine, where carcass fat concentration and P3 fat depth were decreased by 10 and 26%, respectively. Other fat depth measurements were not different ($P > 0.15$) from those of control pigs. In addition, pigs consuming the highest betaine level had a 19% increase in the carcass protein:fat ratio, 23% higher carcass protein deposition rate, and a 24% increase in lean gain efficiency compared with controls. Dietary betaine had no effects ($P > 0.15$) on growth performance, visceral tissue chemical composition, carcass fat deposition rate, visceral fat and protein deposition rates, or serum urea and ammonia concentrations. These data suggest that betaine alters nutrient partitioning such that carcass protein deposition is enhanced at the expense of carcass fat and in part, visceral tissue.

Key Words: Betaine, Carcass Composition, Pigs

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Introduction

Betaine is an amino acid (trimethyl-glycine) present in most organisms and is an obligatory intermediate in the catabolism of choline. It is an osmotically active organic solute that accumulates in tissues under water or salt stress (Petronini et al., 1992), has potential lipotropic effects (Finkelstein, 1990; Barak et al., 1993), and can serve as a methyl donor via S-adenosyl-methionine.

Addition of betaine to swine diets has increased since Cadogan et al., (1993) reported a decrease in backfat thickness. Subsequent investigations have yielded variable results of betaine in swine. Betaine increased ADG in finishing pigs fed low protein-low energy diets and adequate protein-high energy diets (Matthews et al., 1998). The same trend was found in finishing pigs fed low-protein diets but not in those fed high-protein diets (Haydon et al., 1995). Smith et al. (1995) also indicated

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that betaine increased ADG and loin eye area in finishing pigs. Recently, Matthews et al. (2001b) reported that addition of betaine to the diet of finishing pigs may result in improved leanness and carcass quality. Other authors (Webel et al., 1995; Øverland et al., 1999) reported no effect of betaine on growth performance or carcass characteristics of finishing pigs. Energy-restricted finishing pigs fed betaine had decreased backfat depth and increased carcass lean percentage (Cromwell et al., 2000). Although positive effects of betaine on growth and feed efficiency are believed to be more readily apparent in feed-restricted finishing pigs, growth and carcass responses have not been investigated in young growing pigs. The objective of this study was to examine the effects of betaine level on growth performance and body composition in young, feed-restricted pigs in the growing phase.

Materials and Methods

Animals and Treatments

A total of 32 crossbred (Landrace × Yorkshire) castrated male pigs from the same farrowing group were used in the study. The Institutional Animal Care and Use Committee of the U.S. Department of Agriculture approved the care and treatment of all pigs. Before the start of the growth trial, all pigs were restrictively fed the control diet at approximately 80% of ad libitum consumption according to the ARC (1981) formula (daily digestible energy intake, MJ = $0.80 \times 55\ [1 - e^{-0.0204 \times BW}]$), between 31 and 36 kg live weight. At 36 kg BW, pigs were randomly allotted to one of four experimental diet groups (0% betaine, 0.125% betaine, 0.25% betaine, or 0.5% betaine; n = 8 pigs/treatment; Betafin, Gladwin A. Read Co., Omaha, NE). Diets were corn-soybean meal-skim milk-based and formulated to contain 18.6% crude protein, 1.2% lysine, and 3.228 Mcal ME/kg (Table 1) to meet or exceed NRC (1998) requirements for all indispensable amino acids and other nutrients.

Beginning at 36 kg BW, pigs were restrictively fed such that the ADFI was similar for all groups (1.7 kg/d; see Table 2). The level of restriction was 69% of predicted ad libitum intake (ARC, 1981). Pigs were fed twice daily (0900 and 1400), and the daily feed allowance was adjusted weekly according to their individual body weights. The pigs were housed in individual pens in an environmentally controlled facility (22°C); water was provided for ad libitum consumption. During the course of the experiment, one pig was removed due to acute bacterial enteritis (0.125% betaine) and a second pig (0.25% betaine) was removed from all analysis due to possible pneumonia (determined at slaughter). Remaining pigs (n = 30) were killed when they reached 64 kg.

Following an overnight fast, pigs were stunned by electrical shock and exsanguinated. Immediately after slaughter, organs and ommental fat were removed and weighed. The contents of the gastrointestinal tract were removed by water gavage and discarded; empty gut and stomach along with the remaining visceral tissues and internal organs were weighed and stored at –20°C.

Table 1. Composition of basal diet (as-fed basis)[a]

Item	%
Ingredients	
Corn	65.03
Soybean meal (48% CP)	18.29
Dried skim milk	12.00
Animal fat (lard)	1.00
Mineral-vitamin mix[b]	2.50
Dicalcium phosphate	1.08
L-Lysine·HCl	0.10
Calculated nutrient composition	
Protein, %	18.59
Fat, %	3.67
Metabolizable energy, Mcal/kg diet	3.23
Crude fiber, %	2.19
Calcium, %	0.97
Phosphorous, %	0.77
Lysine, %	1.20
Methionine, %	0.33
Methionine + Cystine, %	0.63
Tryptophan, %	0.22
Threonine, %	0.75
Arginine, %	1.12
Isoleucine, %	0.76
Leucine, %	1.65
Histidine, %	0.45
Valine, %	0.91
Phenylalanine, %	0.90
Glycine, %	0.65
Choline, mg/kg	1,088

[a]Diets prepared by United Feeds Inc.

[b]Provided the following amounts per kilogram of feed: Zn, 100.4 mg; Fe, 128.3 mg; Mn, 43.2 mg; Cu, 6.7 mg; I, 0.88 mg; Co, 0.34 mg; Se, 0.26 mg; vitamin A, 4000 IU; vitamin D, 800 IU; vitamin E, 17 IU; vitamin B_{12}, 0.02 mg; vitamin K, 1.9mg; riboflavin, 8.3 mg; D-pantothenic acid, 21.3 mg; niacin, 43.0 mg; choline, 1,088 mg; thiamine, 3.4 mg; pyridoxine, 6.9 mg; folic acid, 0.39 mg; biotin, 0.15 mg ; Na, 2.6 g.

The right side of each carcass was hung overnight at 4°C, and standard measurements were taken the following morning. Area of the longissimus muscle was determined by drawing the longissimus muscle surface area at the 10th rib on tracing paper. The outline was then traced using translucent digitizing tablet (Neumonics Corp., Model 2210, Montgomeryville, PA). The area of the digitized tracing was calculated using Sigma-Scan software Version 3.90 (Jandel Scientific, Sigma-Scan, Corte Madera, CA). Tenth-rib fat thickness was determined by measuring the fat thickness perpendicular to the outer skin surface, at three levels over the longissimus muscle (P1, 40mm; P2, 60mm; P3, 80mm from the midline). Midline backfat thickness at the first rib, last rib, and last lumbar vertebra was also determined at this time. The right side of each chilled carcass and the frozen visceral tissue were ground separately (model 810 GH; Autio Inc., Astoria, OR) four times, and representative samples were stored at –20°C until analysis. Prior to chemical analysis, tissue sam-

Table 2. Effect of dietary betaine levels on growth performance of growing pigs[a]

Item	Betaine 0%	0.125%	0.25%	0.5%	Pooled standard error	Linear regression Slope	P-value
Initial weight, kg	36.2	36.1	36.1	36.1	0.12	0.013	0.967
Final weight, kg	64.0	64.0	64.1	64.3	0.57	0.585	0.679
Feed Intake, kg/d	1.72	1.69	1.71	1.72	0.018	0.070	0.882
Days on treatment	59.8	59.9	56.6	56.8	2.8	–6.85	0.324
Average daily gain, g/d	475	472	501	499	21.8	57.0	0.299
Feed/gain	3.70	3.63	3.50	3.46	0.17	–0.482	0.271
Empty body weight, kg[b]	56.6	56.4	56.6	57.1	0.47	1.11	0.345
Carcass, kg	44.1	43.9	44.2	44.5	0.44	0.940	0.392

[a]Values are means ± pooled standard error (n = 8 pigs/group, 0 and 0.5% betaine; n = 7 pigs/group, 0.125 and 0.25% betaine).
[b]Empty body weight is whole animal weight without the contents of gastrointestinal tract.

ples were cooled in liquid N_2 and powdered in a stainless steel juicer (Vita Mix Corp., Cleveland, OH) in the presence of dry ice to ensure uniform samples.

Serum Collection and Analysis

Blood samples were collected (venous puncture via anterior vena cava), on d 35 at 3 h after feeding and on the day of slaughter following a 16-h fast. After collection, the blood samples were placed on ice for 1 h and centrifuged for 30 min at 2,000 *g*. Serum was harvested, recentrifuged, and frozen (–20°C) until subsequent analysis for urea and ammonia N. Urea and ammonia nitrogen in serum were analyzed spectrophotometrically using the urease method (Sigma, St Louis, MO; kit #535-B).

Linear regression analysis was performed using dietary betaine addition as the independent variable (STATGRAPHICS Plus for Windows Version 2.0, Manugistics Inc., Rockville, MD). Data are presented as treatment means ± pooled standard error with linear slopes and corresponding *P*-values. Effects were considered significant at $P < 0.05$ and trends were considered for $P < 0.10$.

Analytical Techniques

Dry weight and ash were determined gravimetrically after heating powdered samples to 100°C for 18 h and to 450°C for 36 h, respectively. Lipid was determined gravimetrically following extraction by the method of Folch et al. (1957). Nitrogen content was determined by the combustion method (model LECO CN-2000 macro Carbon/Nitrogen Determinator, St. Joseph, MI) and protein was estimated as 6.25 × N content.

Deposition rates of carcass protein and fat were calculated by comparative slaughter technique based on assumed body composition of pigs at the start of the growth trial. We based our calculations for initial body composition for the animals in this study on a similar group of pigs from a study conducted earlier in this laboratory (31 kg crossbred Landrace pigs; see Caperna et al., 1994). We assumed that at the start of this study the carcass of 36 kg live weight pigs were 71% of the live weight and contained 195 and 138 g/kg of protein and fat, respectively. Viscera was assumed to represent 10.9% of the live weight and contain 162 and 65 g/kg of protein and fat, respectively. Lean and fat gain efficiencies were derived from dividing protein or fat deposition rates, respectively, for carcass and viscera, by daily feed intake.

Results and Discussion

Growth Performance. Dietary betaine had no influence ($P > 0.15$) on growth rate or the feed:gain ratio in feed-restricted pigs growing from 36 to 64 kg (Table 2). In addition, empty body and carcass weights were similar for all treatment groups ($P > 0.15$). These data are consistent with the results of other studies, which indicated that there was no effect of dietary betaine on overall growth performance (Matthews et al., 1998, 2001b; Øverland et al., 1999). Cera and Schinckel (1995) reported a decrease in feed:gain ratio in finishing gilts but not in barrows, and Matthews et al. (1998) suggested that an interaction between betaine, crude protein, and net energy on ADG might exist in the early and late finishing periods; this could explain some of the conflicting results reported in the literature.

Carcass Traits. In this study, the concentration (g/kg DM) of fat in the carcass was lower in pigs consuming betaine than in controls and decreased linearly ($P = 0.060$) with increasing levels of dietary betaine (Table 3). Compared with controls, pigs consuming 0.5% betaine had a 10% lower concentration of carcass fat. Fat depth at the P3 site (Table 4) reflected a linear trend ($P = 0.141$) toward reduced fat as the concentration of dietary betaine increased. Compared with controls, 0.5% betaine pigs tended to have 26% lower P3 values. Other linear measurements of backfat depth at other locations were not different ($P > 0.15$) between groups of pigs. There was a linear trend toward increased total carcass protein ($P = 0.124$) as the concentration of dietary betaine was increased (Table 3). Compared with controls, 0.5% betaine pigs had approximately 540 g

Table 3. Effect of dietary betaine levels on chemical composition of carcass and visceral tissue of growing pigs[a]

Item	Betaine 0%	0.125%	0.25%	0.5%	Pooled standard error	Linear regression Slope	P-value
Carcass fat, g/kg, DM	481	454	447	434	18.0	–87.6	0.060
Carcass fat, total, g	8,671	7,896	7,994	7,935	456	–1,165	0.317
Carcass H_2O, g/kg	593	604	596	591	9.18	–9.47	0.682
Carcass ash, g/kg, DM	86.5	91.2	81.1	89.8	4.45	2.89	0.804
Carcass protein, g/kg, DM	452	479	454	477	19.2	3.38	0.489
Carcass protein, total, g	8,063	8,320	8,113	8,605	243	966	0.124
Carcass protein:fat ratio	0.96	1.07	1.02	1.13	0.080	0.305	0.135
Viscera fat, g/kg, DM	443	413	440	411	19.9	–48.2	0.328
Viscera fat, total, g	798	695	778	693	57.0	–15.7	0.286
Viscera H_2O, g/kg	701	710	704	709	8.47	12.98	0.517
Viscera ash, g/kg, DM	31.7	34.3	32.6	34.0	1.20	3.31	0.291
Viscera protein, g/kg, DM	499	535	521	523	1.95	3.17	0.524
Viscera protein, total, g	882	897	914	870	31.8	–26.8	0.738
Viscera protein:fat ratio	1.16	1.32	1.19	1.30	0.094	0.20	0.404

[a]Values are means ± pooled standard error (n = 8 pigs/group, 0 and 0.5% betaine; n = 7 pigs/group, 0.125 and 0.25% betaine).

more total carcass protein. Additionally, the protein:fat ratio in the carcass increased numerically with dietary betaine addition, from 0.96 for controls to 1.13 for 0.5% betaine pigs ($P = 0.135$). Dietary betaine had no apparent influence ($P > 0.15$) on carcass water and ash concentration. The decreased carcass fat concentration agrees with earlier studies on finishing pigs, in which dietary betaine (0.1 and 0.125%) was associated with decreased backfat thickness (Cadogan et al., 1993; Virtanen and Campbell, 1994; Lawrence et al., 1995). In addition, finishing pigs consuming betaine between 0 and 0.5 % had decreased 10th rib backfat thickness (Matthews et al., 2001b). Increased loin eye area reported previously (Cadogan et al., 1993; Smith et al., 1995) in finishing pigs fed commercial diets, agrees with our finding of increased total carcass protein. Other reports have indicated that betaine (0.125 and 1.05%) has no influence on carcass fat or protein (Matthews et al., 1998; Øverland et al., 1999) in finishing pigs. These latter studies were performed using pigs fed either ad libitum or were less feed-restricted than in the present experiment. Furthermore, Matthews et al. (1998) found that betaine was associated with increased carcass lipid content in pigs fed high-net-energy diets. Although a direct comparison between ad libitum and restrictively fed pigs was not performed in the present experiment, the lean genotype of pigs and the restricted feeding regimen used appear to have contributed to positive responses of betaine on carcass fat and protein.

Viscera Traits. A negative linear trend was observed for total viscera ($P = 0.129$) and small intestine weight ($P = 0.114$) as the concentration of dietary betaine was increased (Table 5) from 0 to 0.5% betaine. However, small intestine weight was increased by 11% in pigs fed diets supplemented with 0.125% betaine. No other individual internal organs were affected ($P > 0.15$) by dietary betaine, which is consistent with Matthews et al. (1998), who also found no differences in liver, kidney, or heart weights of pigs fed 0.125% betaine.

Table 4. Effect of dietary betaine levels on linear measurements of back fat thickness and loin eye area of growing pigs[a]

Item	Betaine 0%	0.125%	0.25%	0.5%	Pooled standard error	Linear regression Slope	P-value
Loin eye area, cm^2	25.8	25.7	26.7	26.9	1.01	2.50	0.356
Tenth-rib backfat thickness, mm							
P1 (40mm)	6.0	6.9	7.6	6.0	0.87	–0.22	0.922
P2 (60mm)	7.6	5.9	7.4	6.5	1.33	–1.26	0.708
P3 (80mm)	7.8	6.1	7.3	5.8	0.84	–3.20	0.141
Midline backfat depth, mm							
First rib	23.1	21.7	26.5	23.0	3.00	1.27	0.868
Last rib	7.8	7.3	10.1	7.0	1.35	–0.807	0.820
Last lumbar	8.4	6.7	8.6	7.6	1.29	–0.481	0.883
Average	13.1	11.9	15.1	12.5	1.46	–0.0077	0.998

[a]Values are means ± pooled standard error (n = 8 pigs/group, 0 and 0.5% betaine; n = 7 pigs/group, 0.125 and 0.25% betaine).

Table 5. Effect of dietary betaine levels on organs and total viscera weight (relative to empty body weight) of growing pigs[ab]

Item	Betaine 0%	0.125%	0.25%	0.5%	Pooled standard error	Linear regression Slope	*P*-value
Liver	1.81	1.86	1.91	1.88	0.055	0.141	0.316
Heart	0.511	0.501	0.493	0.498	0.023	−0.023	0.687
Kidneys	0.409	0.402	0.448	0.408	0.017	0.010	0.824
Small intestine	2.06	2.29	2.01	1.98	0.070	−0.326	0.114
Large intestine	1.79	1.76	1.73	1.64	0.093	−0.291	0.213
Stomach	0.742	0.724	0.742	0.706	0.029	−0.064	0.377
Bladder	0.0872	0.0838	0.0656	0.0814	0.010	−0.014	0.590
Spleen	0.171	0.175	0.192	0.181	0.010	0.022	0.376
Viscera	11.0	11.2	10.9	10.7	0.21	−0.802	0.129

[a]Values are means ± pooled standard error (n = 8 pigs/group, 0 and 0.5% betaine; n = 7 pigs/group, 0.125 and 0.25% betaine).

[b](Weight/empty body weight) × 100.

The energy expenditure per unit weight of liver, kidney, and gastrointestinal tract is higher than that of the body as a whole (Blaxter, 1989). Although the overall decrease in whole viscera weight as a function of dietary betaine was small in the present study, it is possible that betaine could play an energy-sparing role under certain conditions. A reduction in the energy requirements for maintenance was found when growing barrows were restrictively fed a corn-soybean diet supplemented with 0.125% betaine (J. W. Schrama and W. J. J. Gerrits, unpublished data). The mechanism underlying the reduction in energy requirements for maintenance after betaine supplementation remains unknown.

Analysis of the chemical composition of visceral tissue revealed no differences ($P > 0.15$) in protein, fat, water, or ash between treatment groups. The composition of carcass and visceral tissue (Table 3) of betaine-fed pigs has not been previously reported.

Serum Metabolites. As expected, serum urea and ammonia N concentrations from samples in the fasting state were lower ($P < 0.001$) than respective samples from fed animals. The concentrations of urea and ammonia in serum from fed or feed-deprived pigs were not influenced ($P > 0.15$) by the betaine content of the diet (Table 6). Coma et al. (1995) reported that N retention and urea N concentration were reflective of one another, such that urea N is minimized as N retention is maximized. Urea concentration in serum did not appear to reflect the increase in carcass protein deposition rate we observed as the betaine level in the diets were increased from 0 to 0.5%. Plasma urea was not altered in finishing pigs fed betaine at similar levels (Matthews et al., 2001b). In contrast, Matthews et al. (1998), indicated that betaine decreased serum urea N in fed pigs during the late finishing period, with no apparent effect on growth and carcass characteristics, although a betaine × protein level interaction was reported.

Estimated Fat and Protein Deposition Rates. The rate of protein deposition in the carcass (Table 7) tended to be linearly related to the dietary betaine content ($P = 0.098$) and lean gain efficiency also was numerically improved by dietary betaine ($P = 0.115$). Compared with controls, 0.5% betaine pigs had 23% higher carcass protein deposition rate and 24% higher lean gain efficiency. Deposition of viscera protein was not influenced ($P > 0.15$) by dietary betaine, nor was the fat deposition rate or fat gain efficiency in either the carcass or the viscera.

There are indications that betaine may play a role in lipid metabolism. Betaine lowered plasma free fatty acids concentrations in untrained Thoroughbred horses (Warren et al., 1999), prevented alcoholic fatty liver in rats (Barak et al., 1993, 1994) and decreased backfat thickness in pigs (Cadogan et al., 1993; Virtanen and Campbell, 1994). It has also been suggested that the effect of betaine on fat and protein accretion may be mediated more through allocation of amino acids between lean growth, visceral growth, and metabolic breakdown than by lipid metabolism per se (Virtanen and Campbell, 1994). Our findings of increased protein deposition rate (Table 7) with unchanged serum urea concentration (Table 6) and nitrogen excretion (unpublished results) support the hypothesis of the role of betaine as a partitioning agent.

Dietary betaine has been shown to stimulate liver lipid mobilization and alter the blood lipoprotein profile (Turpin, 1985; Barak et al., 1994). Furthermore, betaine may serve as an important alternative methylating agent when normal methylating pathways are impaired by ethanol ingestion, drugs, or nutritional imbalances (Barak and Tuma, 1983). A possible mode of action of methyl donors involves a methionine sparing effect in processes, such as the methylation of nucleic acids and other substrates (e.g., synthesis of carnitine, creatine, phosphatidylcholine) that requires methyl group transfer only from S-adenosyl-methionine, freeing additional methionine for other metabolic functions (Kidd et al., 1997). Puchala et al. (1998) reported increased plasma methionine levels when calves were duodenally infused with betaine and Campbell et al. (1995) suggested that betaine partially replaces methionine in sulfur amino acid-deficient diets fed to finishing pigs. In contrast,

Table 6. Effect of dietary betaine levels on serum urea and ammonia concentrations of growing pigs fed or feed-deprived[ab]

Item	Feeding state	Betaine 0%	Betaine 0.125%	Betaine 0.25%	Betaine 0.5%	Pooled standard error	ANOVA Betaine	ANOVA Fed vs deprived	ANOVA Betaine × state
Urea, mg N/dL	Fed	16.3	16.8	15.6	16.9	0.84	0.8113	0.0001	0.9309
	Fasted	11.5	11.8	11.3	11.4	0.92			
Ammonia, mg N/dL	Fed	1.16	1.35	1.58	1.44	0.17	0.4401	0.0001	0.3973
	Fasted	0.66	0.65	0.65	0.64	0.032			

[a]Values are means ± pooled standard error (n = 8 pigs/group, 0 and 0.5% betaine; n = 7 pigs/group, 0.125 and 0.25% betaine).
[b]Fed samples were collected on d 35 from pigs 3 h after morning feeding (average weights ± pooled standard error for each group were: 0% betaine 49.2 ± 1.2; 0.125% betaine 48.9 ± 1.2; 0.25% betaine 50.7 ± 1.1; 0.5% betaine 50.9 ± 3.0). Feed-deprived samples were collected at slaughter following a 16 h deprivation; animal weights and collection day are given in Table 2.

betaine did not spare methionine in weanling pigs (Matthews et al., 2001a). Addition of betaine (0.34%) to methionine-deficient diets increased the activity of hepatic betaine-homocysteine methyltransferase (**BHMT**), which catalyzes transfer of one methyl group from betaine to homocysteine to yield methionine, whereas methionine deficiency per se did not increase BHMT activity in pigs (Emmert et al., 1998). This contrasts to reports for rats and chickens in which methionine deficiency increased hepatic BHMT (Finkelstein et al., 1982; Emmert et al., 1996). Furthermore, under conditions of adequate dietary methionine, pigs seem to have a higher activity of hepatic and renal BHMT than do rats or chicks (Emmert et al., 1998). In the present study, in which a balanced diet was fed at marginal levels of intake, the effects found with the addition of betaine could be caused not only by sparing methionine, but also by other mechanisms as well. According to Øverland et al., (1999) betaine does not affect the apparent overall digestibility of dry matter, total carbohydrate, or N. Thus, the mechanism of action of betaine is likely to be postabsorptive in nature.

In the present study, regression analysis was used to evaluate graded doses of betaine between 0 and 0.5% on growth and body composition, whereas most studies with betaine as a dietary supplement for pigs have utilized either 0.1 or 0.125% betaine. Øverland et al., (1999) did not find a positive effect of 1.0% betaine on growth performance or carcass characteristics when added to a high-fat diet. Matthews et al. (2001b) determined that finishing pigs fed between 0 and 0.5% betaine, improved carcass traits (pork quality, backfat depth, and carcass length) were most evident at 0.25% betaine. In contrast, Cromwell et al. (2000) found that the lower levels of betaine (0.068, 0.114, and 0.182%) were most effective in increasing lean percentage when added to reduced-energy diets. These data indicate that optimal levels of dietary betaine may be dependent upon growth stage and levels of feed intake as well as on dietary components.

We are unaware of literature regarding the effect of dietary betaine on the growth performance and carcass characteristics of young growing pigs in the 30- to 60-kg range; all previously reported experiments have been

Table 7. Effect of dietary betaine levels on fat and protein deposition rate and efficiency of growing pigs[ab]

Item	Betaine 0%	Betaine 0.125%	Betaine 0.25%	Betaine 0.5%	Pooled standard error	Linear regression Slope	Linear regression *P*-value
Carcass protein deposition rate, g/d	52.2	56.3	55.5	64.4	5.52	23.2	0.098
Carcass fat deposition rate, g/d	87.5	73.3	80.3	77.7	8.75	–12.9	0.562
Carcass lean gain efficiency[c]	30.4	33.3	32.2	37.6	3.11	13.3	0.115
Carcass fat gain efficiency[d]	51.0	43.2	47.1	45.3	4.84	–7.55	0.564
Viscera protein deposition rate, g/d	4.1	4.5	4.9	4.0	0.55	–0.31	0.826
Viscera fat deposition rate, g/d	9.4	7.3	9.4	7.7	1.1	–2.1	0.457
Viscera lean gain efficiency[e]	2.4	2.6	2.9	2.3	0.31	–0.19	0.811
Viscera fat gain efficiency[f]	5.5	4.3	4.5	4.5	0.64	–1.25	0.456

[a]Values are means ± pooled standard error (n = 8 pigs/group, 0 and 0.5% betaine; n = 7 pigs/group, 0.125 and 0.25% betaine).
[b]Efficiency as grams of protein or fat accreted per day per kilogram of daily feed intake.
[c]Grams of protein in carcass accreted per kilogram of feed ingested.
[d]Grams of fat in carcass accreted per kilogram of feed ingested.
[e]Grams of protein in viscera accreted per kilogram of feed ingested.
[f]Grams of fat in viscera accreted per kilogram of feed ingested.

performed with finishing pigs. Studies by Cromwell et al. (1999, 2000) suggest that positive effects of betaine as a carcass modifier are better expressed in restrictively fed pigs. However, in those experiments, dietary energy was diluted using wheat middlings, which may contain significant amounts of betaine (Kidd et al., 1997). Furthermore, there is evidence that betaine may increase fatness in pigs fed high-energy diets (Matthews et al., 1998). We designed this experiment under restricted feeding conditions (69% ARC predicted ad libitum intake) with the purpose of investigating net effects of betaine under highly restricted protein-energy intake on growth and body composition.

It is possible that positive effects of betaine on growth performance and on carcass characteristics are evident only under certain conditions, particularly during metabolic or nutritional stress. For example, betaine improved bird performance during coccidiosis (Virtanen et al., 1993; Augustine et al., 1997), plasma lactate concentrations (associated with muscular fatigue) were lower after exercise when untrained horses received betaine (Warren et al., 1999), and growth performance was improved in pigs fed low-energy diets (Cromwell et al., 1999, 2000). Further work is required to better define the conditions for which dietary betaine can provide performance improvement.

Implications

Betaine addition to diets of young growing feed-restricted pigs resulted in a decrease in some measures of carcass fat with a concomitant increase in some measures of carcass protein. These data suggest that betaine alters nutrient partitioning in young feed-restricted pigs such that protein deposition is enhanced at the apparent expense of carcass fat and in part, visceral tissue. Betaine may be useful as a partitioning agent under low amino acid and energy intake situations.

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